NDT&E International 46 (2012) 94–99

Contents lists available at SciVerse ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Using an eddy current method with inverse analysis to determine the thickness of the layer modified by cavitation peening at the surface of type 316 L austenitic stainless steel

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ARTICLE INFO

Article history:
Received 12 July 2011
Received in revised form
18 November 2011
Accepted 21 November 2011
Available online 30 November 2011

Keywords:
Eddy currents
Inverse problem
Residual stress
Stainless steel
Surface modification

ABSTRACT

The depth to which a material is modified by cavitation peening affects the stress corrosion cracking resistance and fatigue properties of the material. Thus, determining the thickness of this modified layer is important for evaluating the peening intensity. In this paper, a nondestructive eddy current method was used to accomplish this. The material under test was stainless steel, AISI 316 L and the thickness of the modified layer, which had a simple stress distribution, was determined by inverse analysis using a surface response methodology. The results demonstrate that the thickness of the layer can be determined by the eddy current method combined with inverse analysis using a response surface methodology.

1. Introduction

The thickness of the layer into which compressive residual stress has been introduced by peening determines the fatigue strength and the stress corrosion cracking (SCC) resistance of the material. To nondestructively evaluate this surface layer, an electromagnetic method is appropriate since the penetration depth can be varied by changing the alternating current frequency.

To enhance the fatigue strength of metallic materials, shot peening (SP) [1], cavitation peening (CP) [2] and other peening methods such as laser peening [3] have been used. In previous papers, an improvement in the fatigue properties and the introduction of compressive residual stress after peening have been reported [1,3,4]. In particular, the thickness of the modified layer where compressive residual stress has been introduced affects the SCC resistance. To evaluate the effects of peening, such as variations in the residual stress, a nondestructive method to examine metallic components is required for use in industry. In the past, the thicknesses of these layers were determined by stress measurements using X-ray diffraction [2] or hardness tests such as indentation methods [4]. Using X-ray diffraction, the surface has to be electrochemically removed at intervals because the X-ray penetration depth is of the order of 10 μm. This requirement means the method is destructive and therefore cannot be applied to industrial components, such as those used in an operational capacity in industrial plants. In the case of hardness tests to determine the thickness, a cross-section of the material is required, which is also destructive. Therefore, considering the depth to which the surface is modified by peening, and that the examination needs to be done on parts to be used in industry, an alternative, nondestructive method to evaluate the thickness is required.

To determine the thickness of the modified layer, the changes in the material properties need to be identified. There are some nondestructive methods for examining material characteristics such as methods using ultrasound [5] or electromagnetic method [6]. Ultrasound is effective for detecting internal cracks or cracks on the back side of metallic materials. However, the penetration depth of general ultrasound method is too large and it is difficult to apply to the measurement of material characteristics that vary gradually with depth into the material. In case of ultrasound method using surface acoustic waves, the penetration depth can be controlled. However, it is hard to conduct evaluation at small area because transmitter and receiver of the ultrasound are required. To characterize the modified layer at the surface of the material, an electromagnetic method is appropriate because the penetration depth can be varied by changing the frequency of the alternating current used, and the test can be conducted nondestructively. The electromagnetic method can vary the measuring area freely with size of measuring equipments like as coils.

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0963-8695/$ - see front matter
doi:10.1016/j.ndteint.2011.11.005

The eddy current method [7] is an effective nondestructive method that can be applied regardless of whether the metal is ferromagnetic or paramagnetic and with which it is possible to vary the penetration depth. It has previously been reported that the electromagnetic parameters, such as the electrical conductivity and magnetic permeability, of metals treated by SP or CP vary [7,8]. The variation in electrical conductivity is derived from piezoresistive effects [9] due to the introduction of stress after peening [7]. Abu-Nabah et al. used an eddy current method and showed that the electrical conductivity varied after the introduction of stress after SP treatment [7]. Abu-Nabah and Nagy showed that the depth to which compressive residual stress had been introduced after peening can be determined by the eddy current method [10]; however, a frequency greater than 1 MHz has to be used for paramagnetic materials such as nickel-based superalloy, in order to achieve sufficient penetration depth. The higher measurement frequency causes noise and capacitance effects when the eddy current frequency is higher than the resonance frequency of the coil. It is difficult to determine the peening efficiency and the thickness of the modified layer because inverse analysis of the eddy current signal requires a theoretical calculation to determine the material properties. On the other hand, reducing the measurement frequency reduces the eddy current density in the material under test [11]. Thus, an appropriate measurement frequency should be selected for the experimental method. The thickness of the modified layer can be determined from various electromagnetic properties obtained using the eddy current method. Considering that the thickness of the modified layer is determined using experimental results combined with calculation, inverse analysis is required. However, a large amount of calculation may be needed in the case of inverse analysis. The inverse analysis used in the present study was conducted using a response surface methodology [12]. This is used to obtain relationships between the input and output in order to predict and approximate the resultant output from a given input. It is assumed that the response can be approximated by a polynomial, and the variables used in the polynomial are determined from the experimental design. Using response surface methodology for the inverse analysis, the solution can be obtained with less calculation than other inverse analysis methods. Thus, an appropriate measurement frequency and the parameters for the inverse analysis should be selected to conduct a precise determination of the thickness of the modified layer with a response surface methodology.

In the case of CP of austenitic stainless steel, AISI 316 L, the compressive residual stress after CP treatment decreases linearly with depth from the surface [2]. In addition, the deformation-induced martensitic transformation is insignificant in the case of AISI 316 L steel [13]. Thus, the eddy current signal is predominantly affected by stress induced by CP, and the effect of the magnetic permeability is negligible because of the lack of phase transformation. The variation in electrical resistivity, the reciprocal of conductivity, need only be considered in the inverse analysis.

In the present paper, to evaluate the peening efficiency in austenitic stainless steel, AISI 316 L, a nondestructive eddy current method with inverse analysis using a response surface methodology was applied to determine the thickness of the layer modified by CP. The results were compared with the results obtained from X-ray diffraction, which showed that the thickness of the modified layer could be accurately determined from the variation in electrical resistivity. Note that this is the first report to determine the thickness of the layer modified by peening using an eddy current and inverse analysis using a response surface methodology based on the variation of the electrical resistivity. To use a response surface methodology for inverse analysis, it can be considered the variation of eddy current signals derived from the depth distribution of the electrical resistivity which is deeper than the penetration depth of the eddy current.

2. Experimental Apparatus and Method

The test material was AISI 316 L austenitic stainless steel which is generally used for pressure tanks and tubes. The thickness, width, and length of the specimens were 6, 100 and 200 mm, respectively. In the present study, to negate the effect on the electromagnetic material properties from the variation in cold work after peening, CP was used as the peening method. Considering that the peening might be applied to large components, a cavitating jet in air was used. The experimental conditions were set as described in a previous paper [2]. A high-speed water jet with pressure of 30 MPa surrounded by a low-speed water jet with pressure of 0.05 MPa was injected into air. The inner diameters of the nozzles for the high-speed and low-speed water jets were 1 mm and 30 mm, respectively. The outer diameter of the nozzle for the high-speed water jet was 16 mm, and the standoff distance, which is the distance from the outlet of the nozzle to the surface of the specimen was set to 45 mm. In the present study, 7 specimens were treated by CP with different processing times. The processing time per unit length, t_p, was determined by the number of scans, n, during CP processing and the CP scanning speed, v, as follows:

$$t_p = \frac{n}{v} \tag{1}$$

t_p was set to 0.25, 0.5, 1, 2, 5, 10 and 20 s/mm. For comparison, an untreated specimen, called the non-peened (NP) specimen was prepared.

The electromagnetic properties were measured using a coil and an LCR meter connected directly to it. The coil reactance, X, was measured considering the variation of the coil resistance with f due to the phase rotation derived from the instrumentation effect. From the additional experiments using the peened and annealed specimen which was used to relieve the residual stress while maintaining the surface roughness, it was shown that the surface roughness had little effect on the eddy current result. The properties of the coil for the eddy current test used in this study are shown in Table 1. The peak-to-peak alternating current generated by the LCR meter was 0.8 mA, and the variation of X with the frequency, f, of the alternating current was measured. Considering the resolution capability of the LCR meter, X at f=100–1000 kHz was used for the inverse analysis.

The penetration depth, δ_p, for an alternating current of frequency f is given by Eq. (2) [11].

$$\delta_p = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2}$$

where μ denotes the magnetic permeability and σ denotes the electrical conductivity.

The resistivity, ρ, of the specimens was calculated using the Dodd-Deeds model [14]. The coil geometry, parameters and

Table 1
Properties of the coil used in the eddy current testing.

Properties	Values
Number of turns N (turns)	240
Wire diameter d_w (mm)	0.1
Outer diameter $2r_2$ (mm)	6.4
Inner diameter $2r_1$ (mm)	3.0
Lift off s (mm)	0.5
Thickness h_{coil} (mm)	2